

Jan. 25, 1966

M. E. HINES

3,231,831

MODE CONTROL IN NEGATIVE RESISTANCE DEVICES

Original Filed Jan. 8, 1960

4 Sheets-Sheet 1

FIG. 1

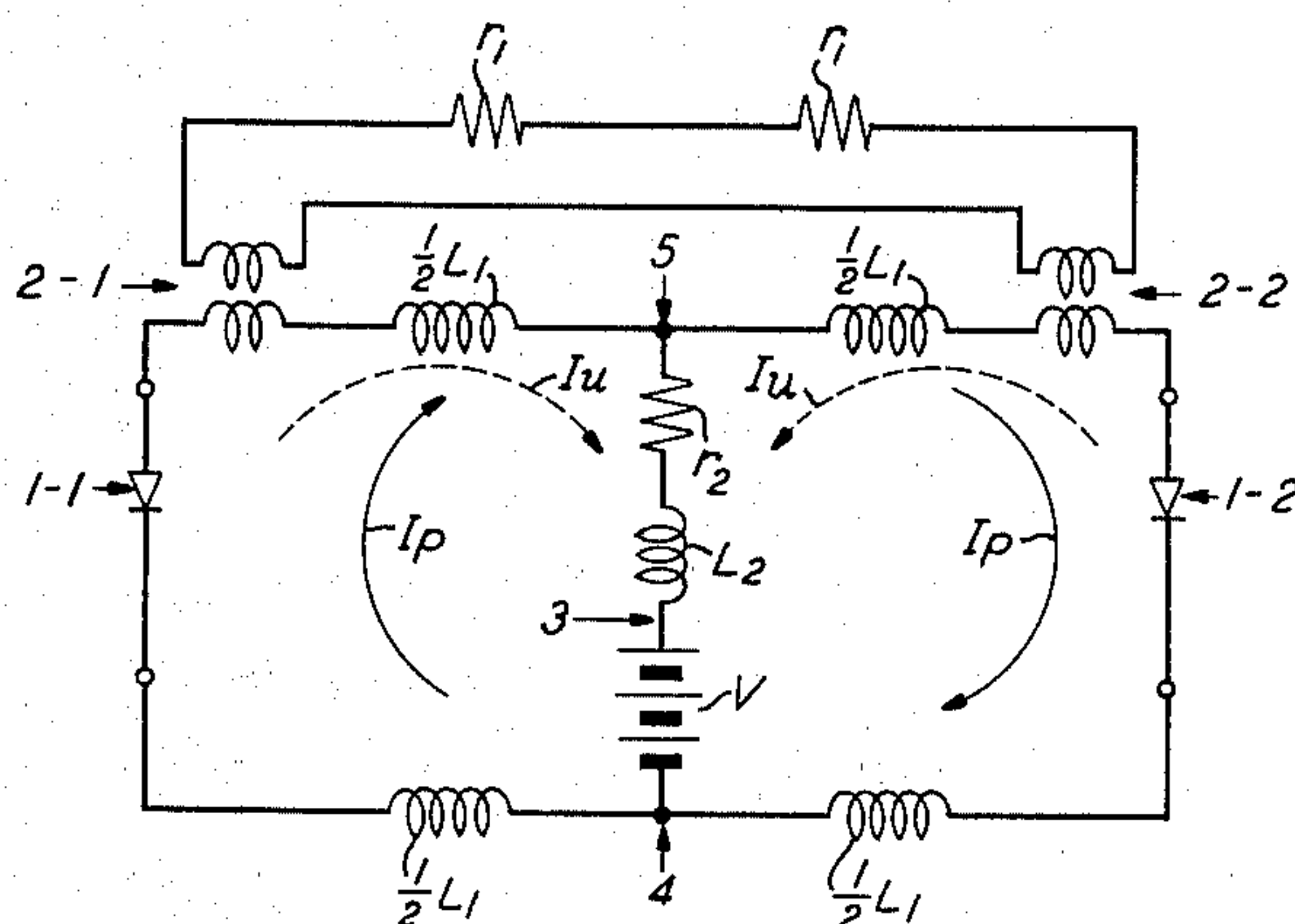


FIG. 2A

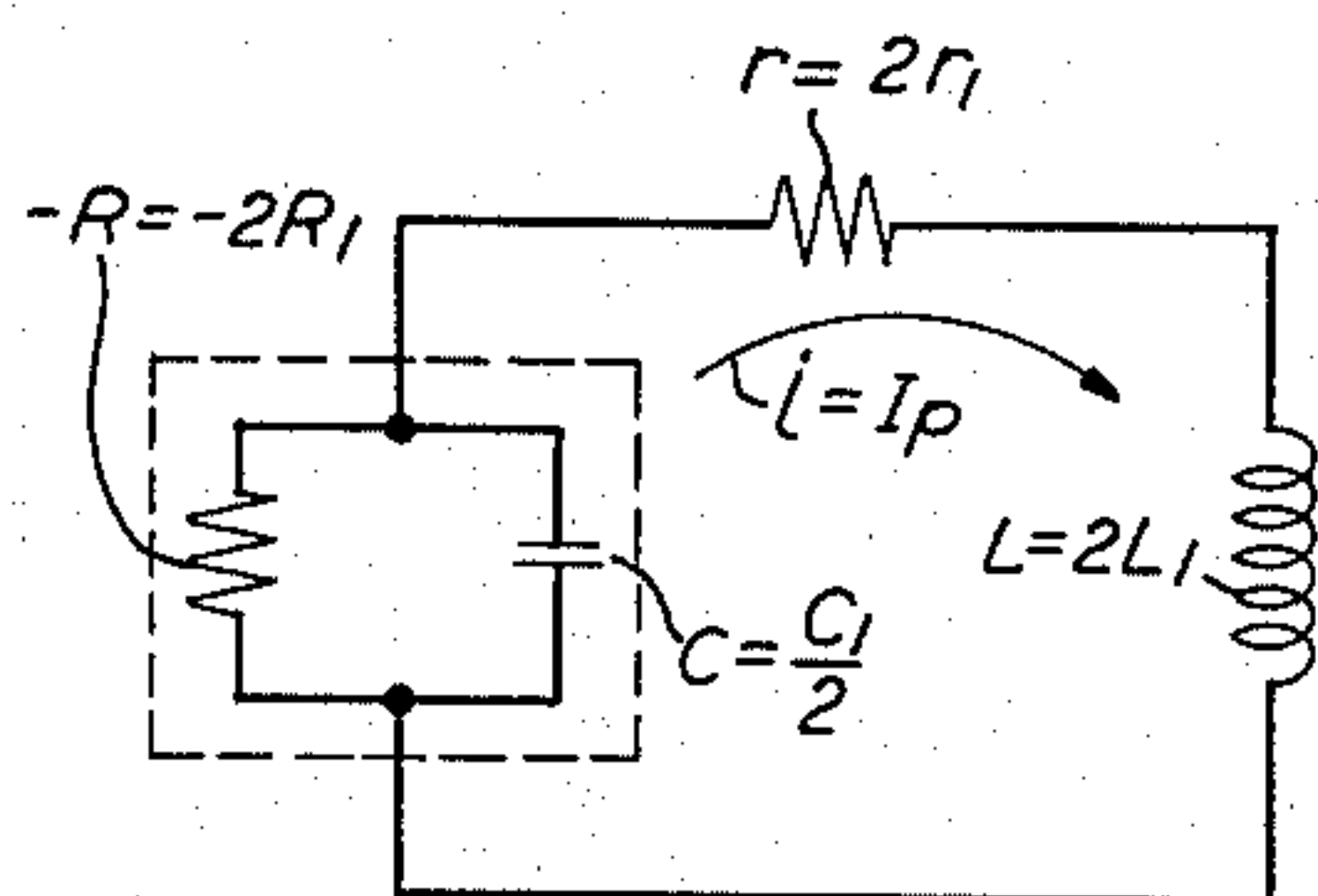


FIG. 2B

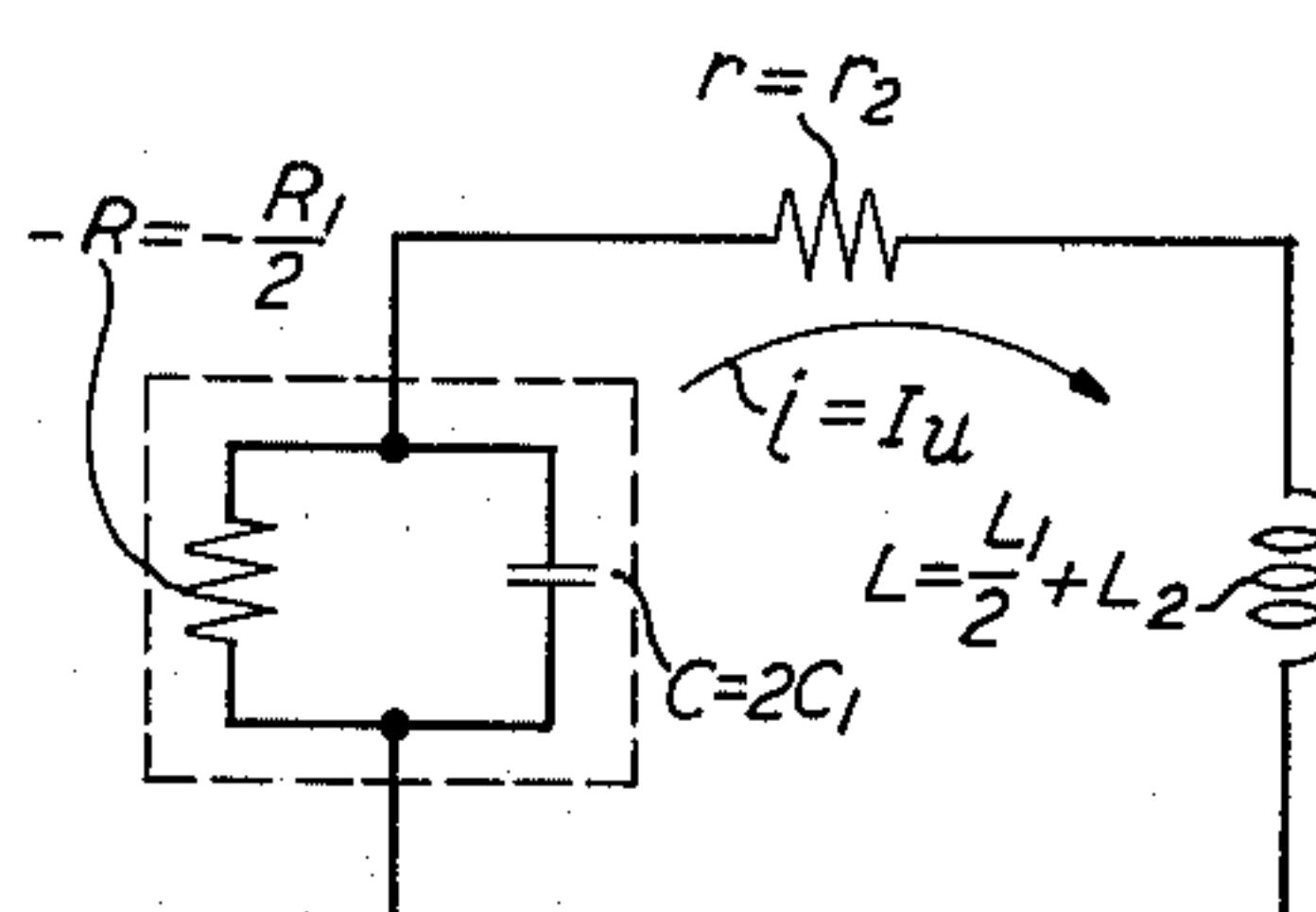
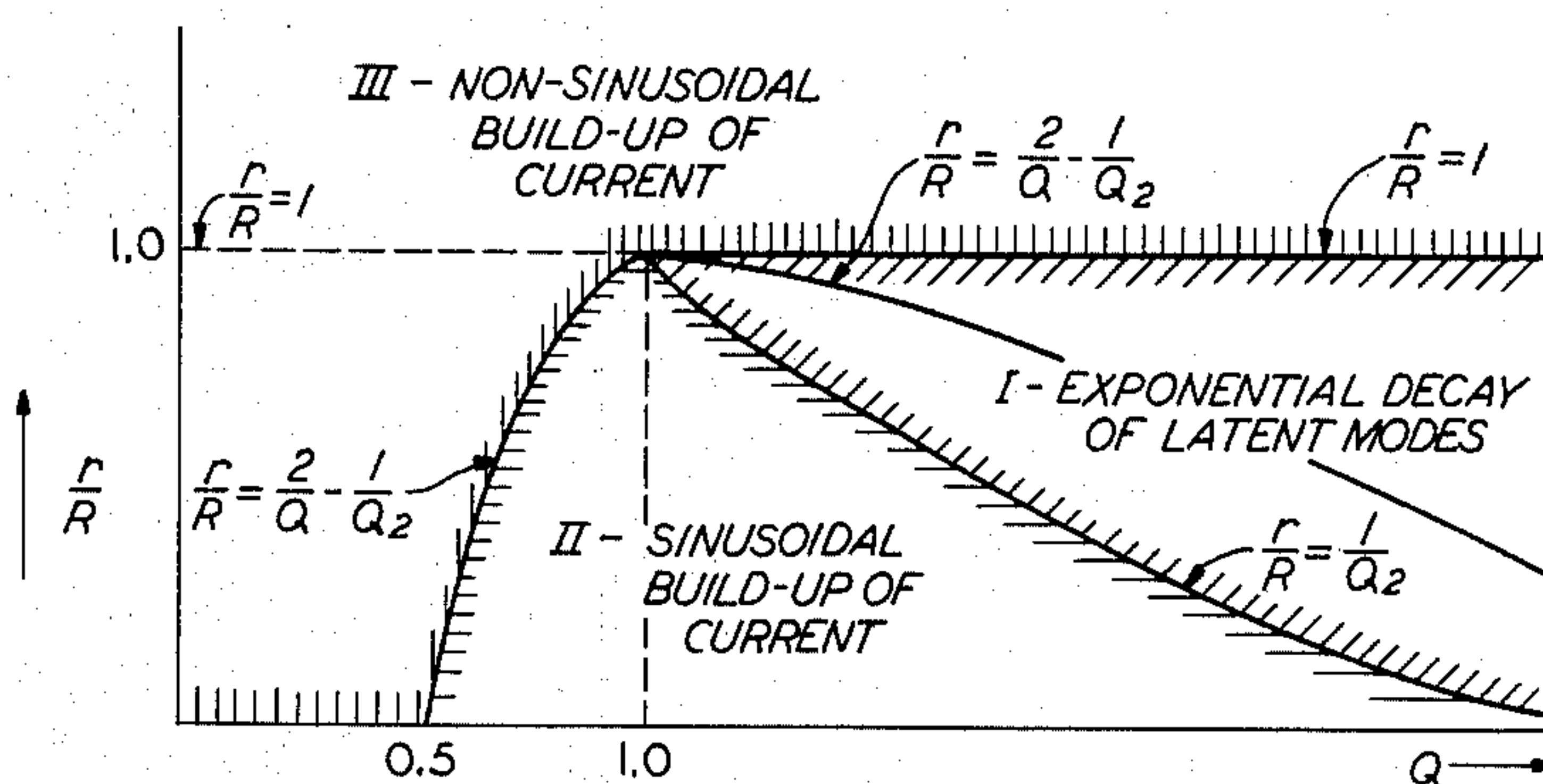


FIG. 3



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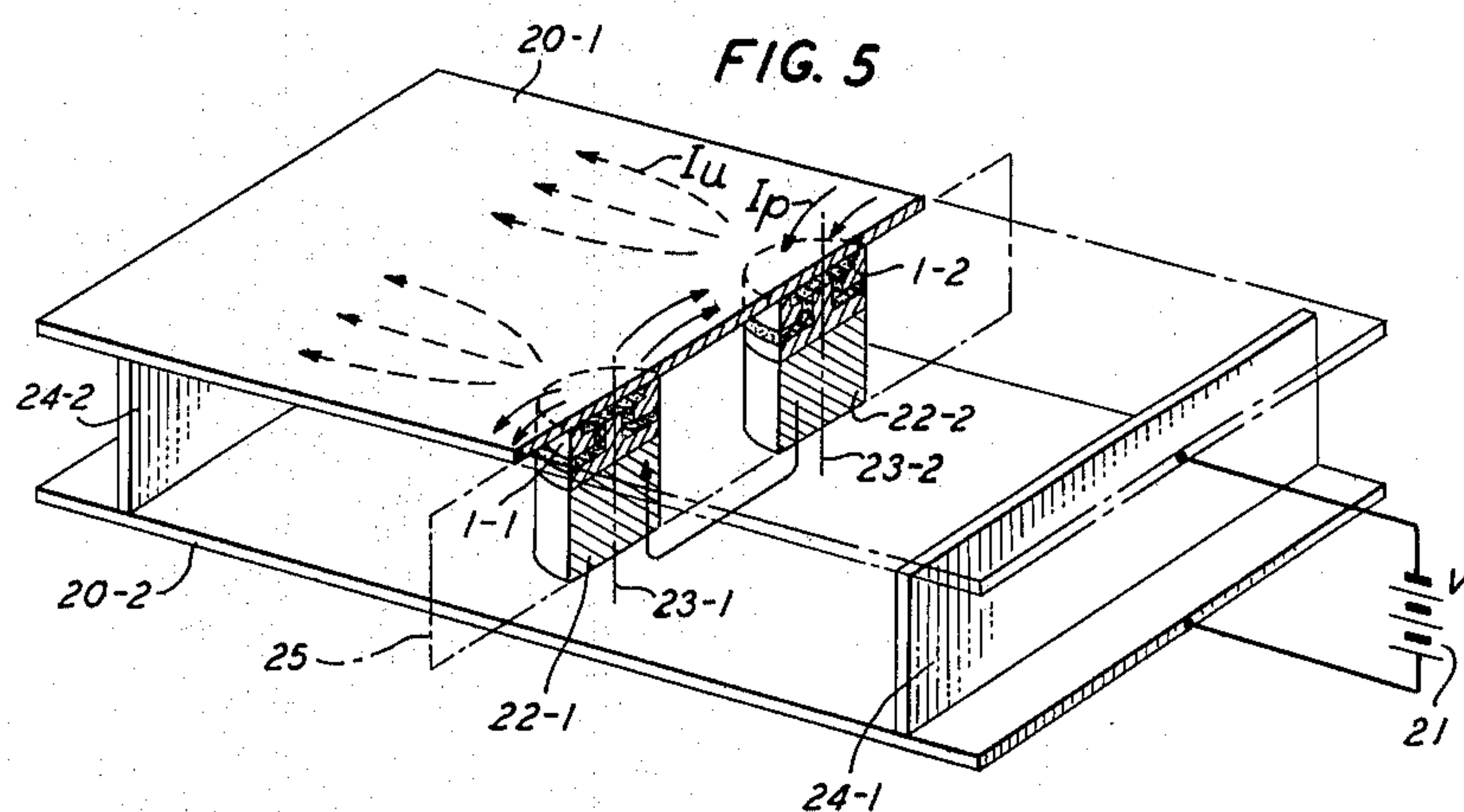
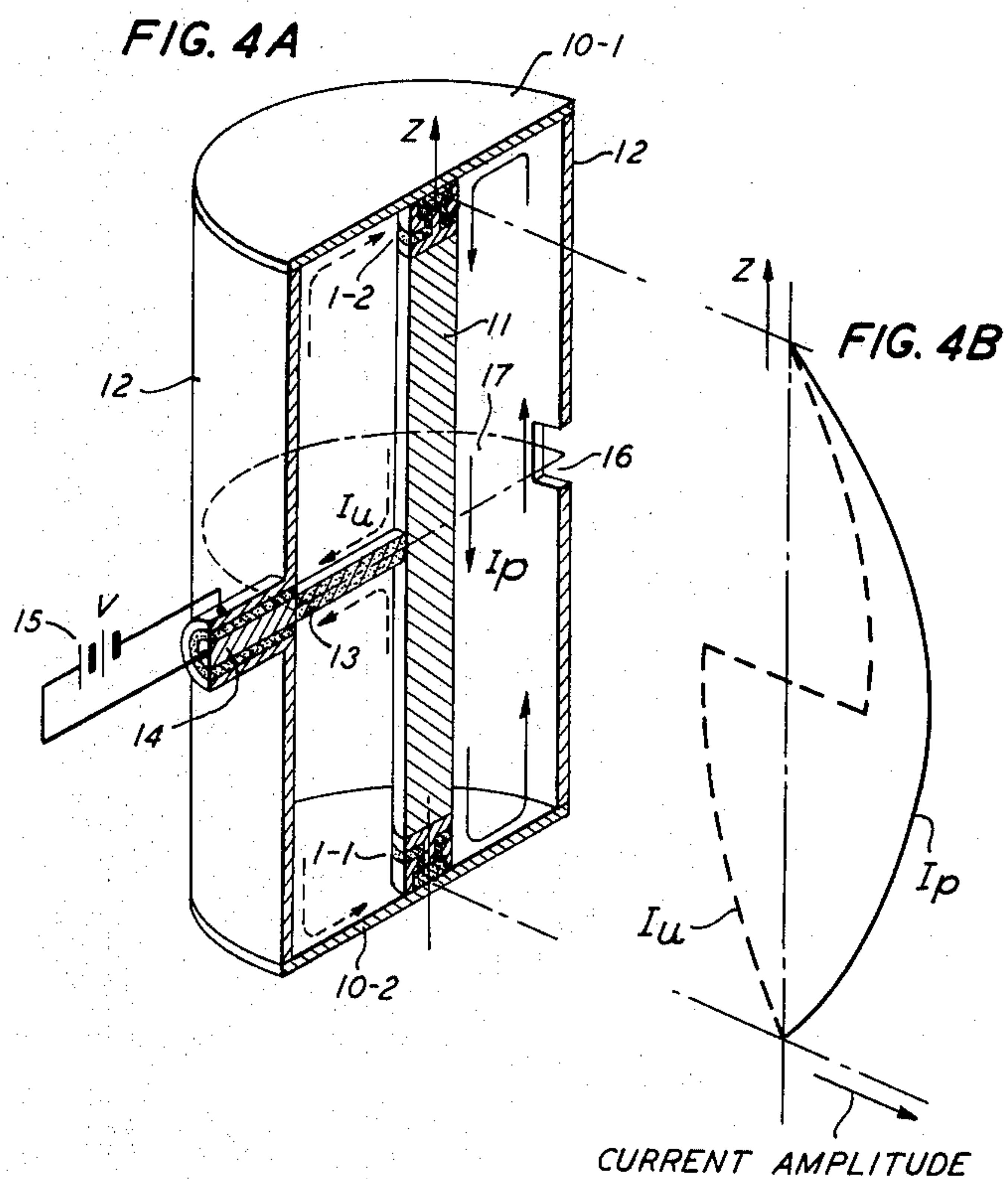
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4 Sheets-Sheet 2



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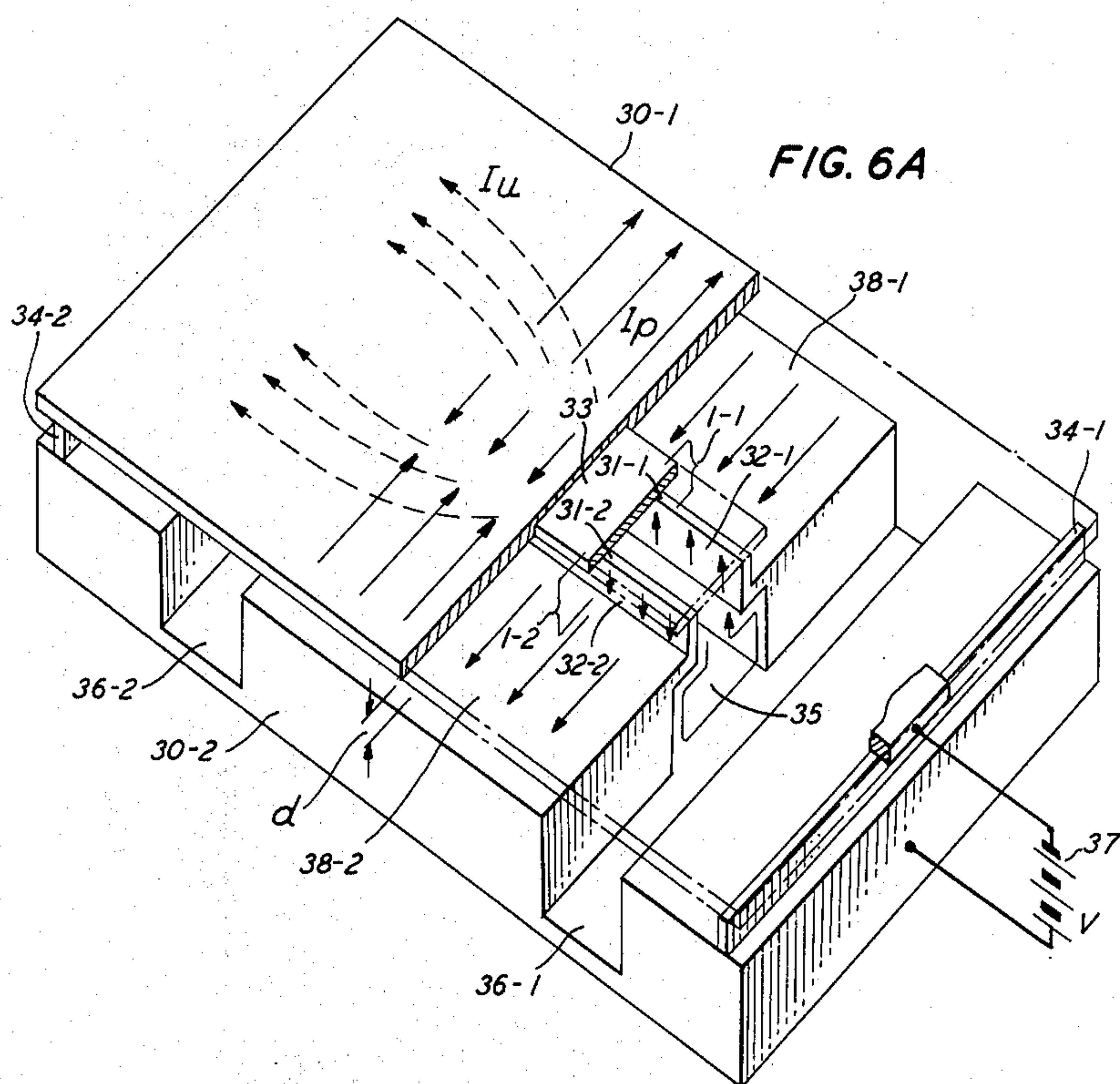
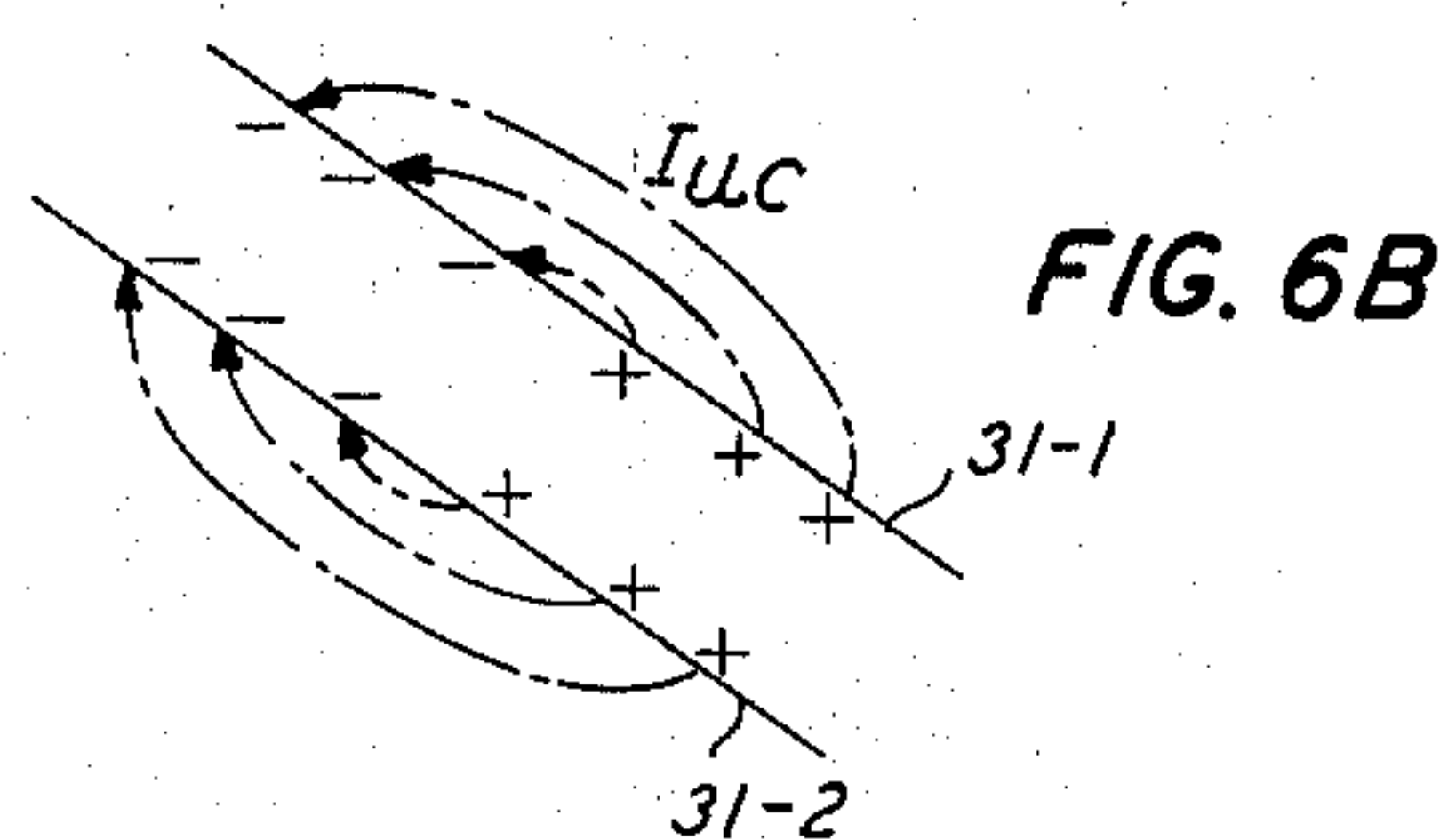
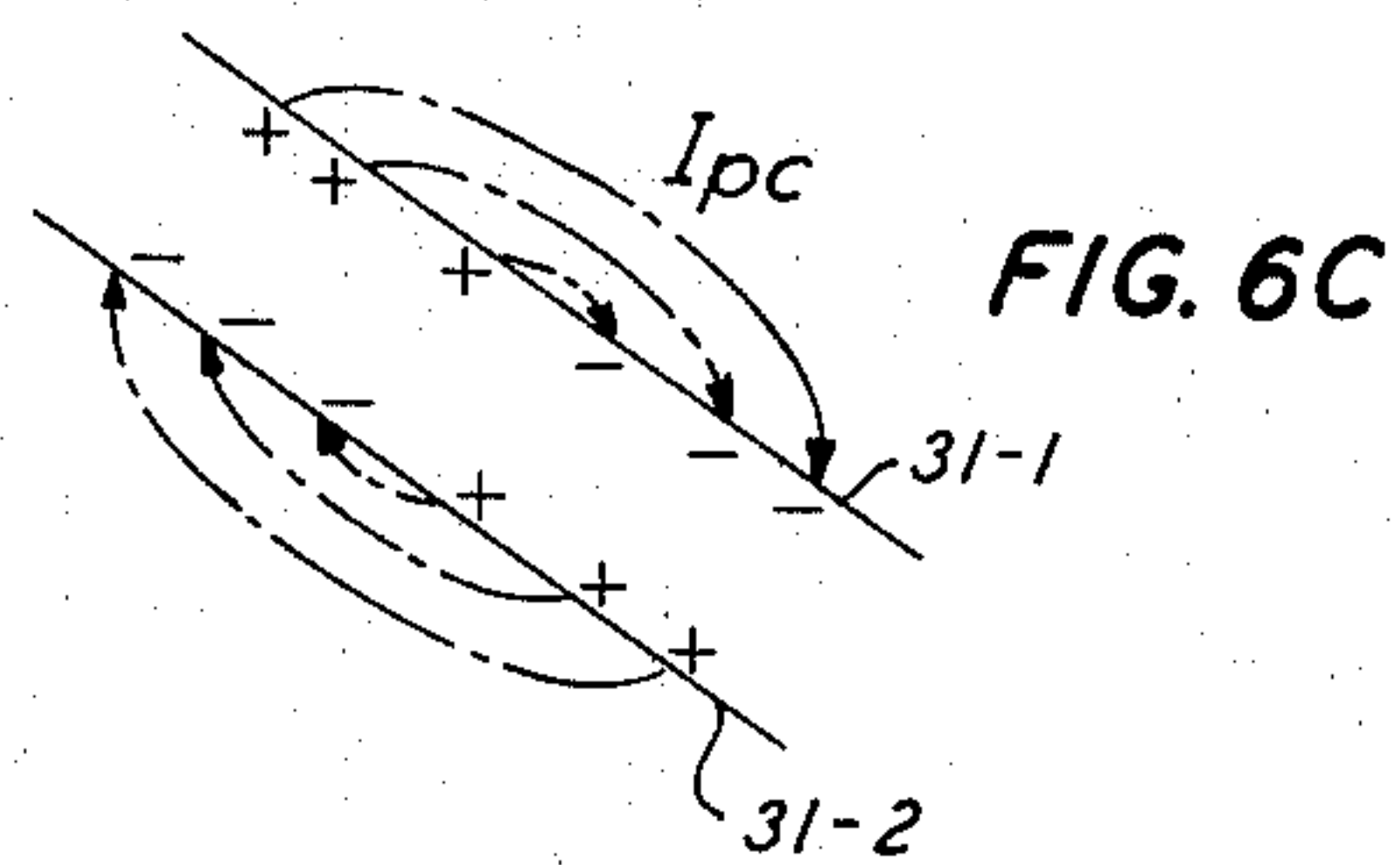
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MODE CONTROL IN NEGATIVE RESISTANCE DEVICES

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4 Sheets-Sheet 3



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Original Filed Jan. 8, 1960

4 Sheets-Sheet 4

FIG. 7

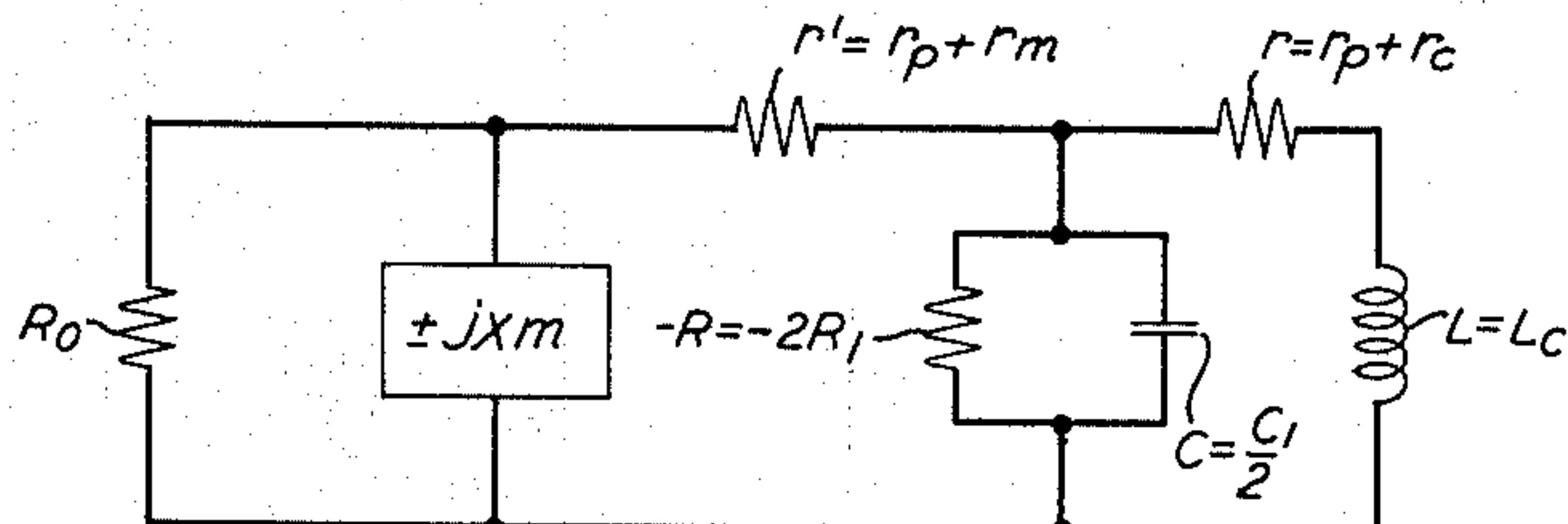
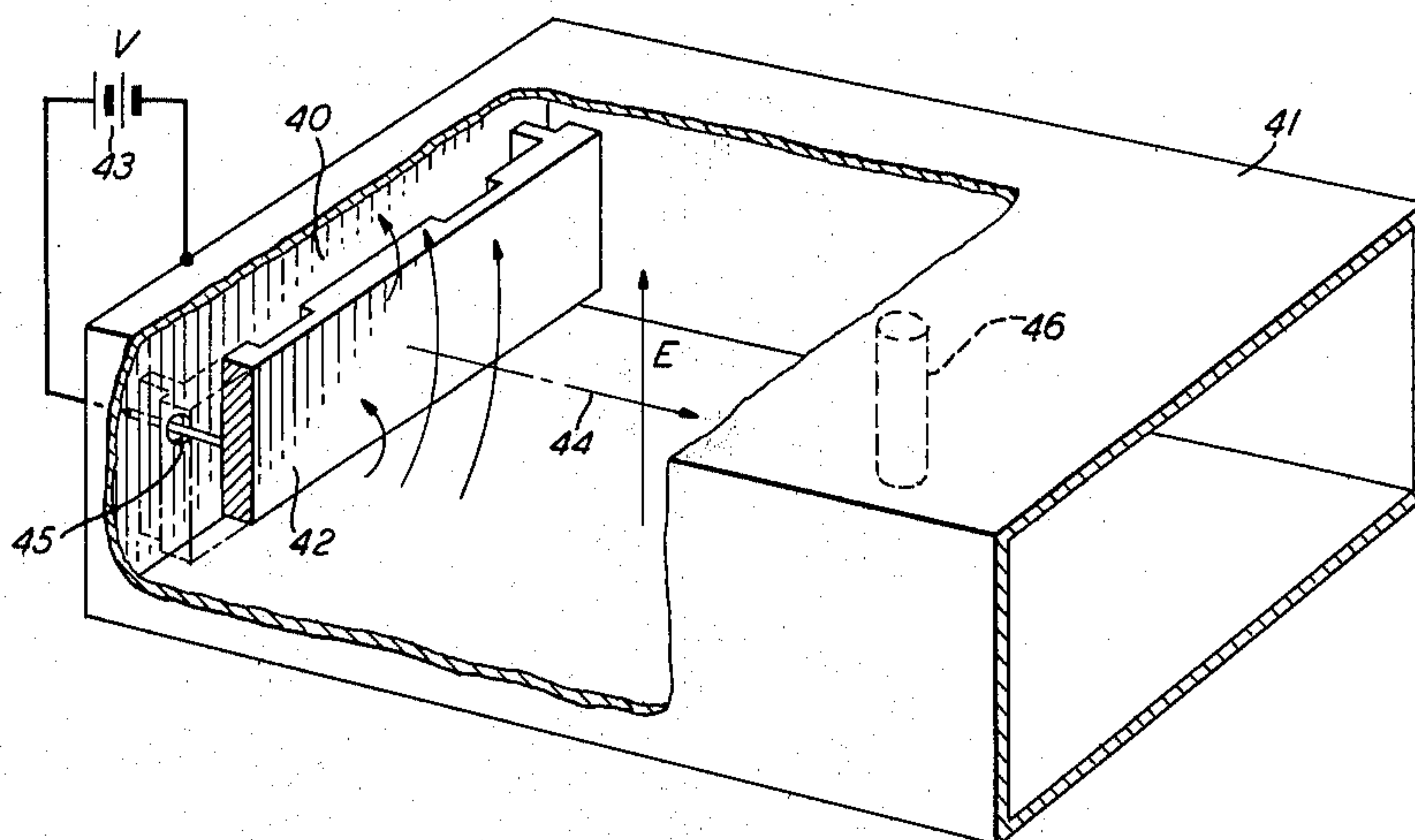


FIG. 8



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1

3,231,831 MODE CONTROL IN NEGATIVE RESISTANCE DEVICES

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Continuation of application Ser. No. 1,212, Jan. 8, 1960.

This application Mar. 21, 1962, Ser. No. 181,357

16 Claims. (Cl. 331-96)

This invention—which stems by continuation from an earlier application, Serial No. 1,212, filed January 8, 1960, now abandoned—relates to the control of multiple modes, particularly in devices employing a multiplicity of negative resistance elements.

In a multielement device the physical separation of its active elements can give rise to a number of distinctive distributions of current and voltage among them, each designated a latent mode. For example, two active elements operating in phase opposition are said to be in the push-pull mode, while the same elements operating in phase coincidence are in the unison mode. Generally speaking, modes have widely separated frequencies, so that active elements able to operate over a restricted frequency range in the vicinity of only one mode are undisturbed by the potential existence of another. However, microminiature configurations of semiconductive devices often have modes that are close together in frequency. And, certain active elements—such as negative resistance diodes of the kind described in the copending application of G. C. Dacey and R. L. Wallace, Jr., Serial No. 855,426, filed November 25, 1959, and issued as U.S. Patent 3,063,023, on November 6, 1962—are operative over an extended range of frequencies.

In any event, the existence of disparate modes makes it possible for one of them to act undesirably as a load upon another or to subordinate it completely. Accordingly, it is an object of the invention to stabilize multielement devices for various operating modes. A related object is the stabilization of devices employing negative resistance diodes.

Negative resistance diodes, and other semiconductive active elements, are often fabricated with internal junctions having minute, i.e., “spot” areas which allow high frequency operation. For such elements, taken separately, this leads to a reduction in power handling capability. Evidently, it is desirable to obtain increased power output in ultrahigh frequency devices without attendant reductions in their operating frequencies, and it is a further object of the invention to do so in devices constituted of negative resistance spot diodes.

Where the microminiaturization achievable with spot diodes is not required, power capability can be greatly augmented without undue frequency restrictions by extending the junctions of the diodes in depth. When several diodes with extended junctions, i.e., “line” diodes, are operated concurrently, a further kind of mode can arise. If the junctions are too long, they can support standing wave modes, which can conflict with the others. Hence, it is a still further object of the invention to stabilize multielement devices having latent standing wave modes, particularly when the elements are negative resistance line diodes.

According to the invention, the foregoing and related objects are achieved by selectively controlling the build-up and decay of the various mode currents in multielement devices. The way in which the modes are controlled depends upon the intended operation of the device. In a stabilized oscillator all modes but one are suppressed. On the other hand, in a stabilized amplifier spurious oscillations are avoided by subjecting all modes to exponential decay. Of course, the latent modes of an amplifier can be selectively suppressed. Some of them can

2

be suppressed well below the thresholds at which oscillations would take place in the absence of mode control. Others can be suppressed only to a degree sufficient to insure stability. In each latter case the mode controlling resistance of a load is so adjusted that the amplifier operates slightly below its threshold of oscillation.

More specifically, with multielement, negative resistance devices mode control relies upon circuit proportions determined by two parameters, which are, respectively (1) a ratio of positive and negative resistances; and (2) an impedance ratio analogous to the so-called “quality” factor of a resonant circuit, except for its inclusion of negative resistance.

A representative configuration illustrating the invention employs two shunt-biased negative resistance diodes that are reactively interconnected.

Acting in concert, the diodes can present negative impedances at diverse mode frequencies. If circuit dimensions are small compared with the free-space wave lengths of potential mode frequencies—in this case, unison, push-pull, and standing wave—the various modes can be separated and their energies controlled. As a result, the negative impedance presented by the diodes can be employed in a wide variety of devices. With an amplifier the negative impedances of all modes are counterbalanced by corresponding load impedances while, for an oscillator, similar balancing is required in all modes but a selected one. For oscillations in the selected mode a net negative impedance is required after all positive impedance has been taken into account.

For example, if a multidiode device is to oscillate in its push-pull mode, an undesired unison mode can be suppressed by resistive means placed in shunt with the diodes at a position in the circuit where it will not interfere with the desired push-pull mode. At low frequencies this is accomplished by placing a resistor in series with a bias supply voltage to form a branch in shunt with both diodes and connected to the mid-point of an inductor interconnecting them. A resistor having a resistance of appropriate magnitude prevents the unison mode from building up.

When a coaxial cavity provides the inductive element interconnecting the diodes of the oscillator, the unison mode is suppressed by a resistive element placed between the inner and outer conductors of the cavity near its mid-section.

To form a strip-line oscillator, either two spot diodes or two line diodes are positioned between extended planar conductors. In the case of spot diodes, the inductive effect is created by currents flowing along the diode axes and establishing a transverse electromagnetic field between the strip-line conductors and in a plane parallel thereto. For a pair of line diodes, the inductive element is provided by a cavity-like region between ridges supporting extended p-n junctions. The energy of the unison mode is attenuated in resistive elements electrically connected between the strip-line conductors and located on the flanks of the diode pair. The major axes of the resistive elements are oriented in the same direction as that characterizing the current flow of the desired push-pull mode so as to have negligible effect on it. To cope with the standing wave modes supportable by the line diodes, the strip-line conductors are closely spaced in the vicinity of the extended p-n junctions. This provides a low inductance path for circulating currents of the standing wave modes, thus raising their frequencies to that part of the spectrum where they may exist only as damped exponentials. The desired damping process is further assisted by the increased skin effect resistance encountered by high frequency circulating currents.

Although the invention may be selectively applied to control any or all of the latent modes, in a wide variety

of circuits, it will be illustrated with oscillator circuits for which the desired operation is in the sinusoidal push-pull mode.

Other aspects of the invention will become apparent after consideration of several illustrative embodiments taken in conjunction with the drawings in which:

FIG. 1 is a circuit diagram of a multielement device employing voltage-controlled negative resistance diodes;

FIGS. 2a and 2b are simplifications of the equivalent circuit of FIG. 1 used in generalizing the operation of a multielement device;

FIG. 3 is a graph setting forth the operating regions of the circuits shown in FIGS. 2a and 2b, as determined by selected circuit parameters;

FIG. 4a is a perspective cross-sectional view of a push-pull diode oscillator employing a coaxial cavity to determine the oscillation frequency;

FIG. 4b is a plot of the axial current distributions supportable by the oscillator of FIG. 4a;

FIG. 5 is a perspective cross-sectional view of a push-pull oscillator having two spot diodes between strip-line conductors;

FIG. 6a is a perspective cross-sectional view of a push-pull oscillator having two line diodes between strip-line conductors;

FIGS. 6b and 6c are plots of the standing wave mode currents supportable by the oscillator of FIG. 6a;

FIG. 7 is a modification of the simplified equivalent circuit of FIG. 2 explanatory of mode suppression in the oscillator of FIG. 6; and

FIG. 8 is a perspective cross-sectional view of the oscillator of FIG. 6 coupled to a waveguide output.

Referring now to FIG. 1, there is presented the circuit diagram of an oscillator incorporating two similarly poled, voltage-controlled negative resistance diodes 1-1 and 1-2 which are taken as alike for simplicity. Respective terminals of the two diodes are interconnected by separate series combinations of two inductors, each having an inductance one-half L_1 . These inductors act in concert with diode capacitance to establish one of the oscillatory modes of the circuit. They are shown as distinct elements in order to indicate that there is no mutual inductive effect between them, thereby making the circuit diagram applicable to the analysis of certain microwave oscillators to be discussed herein. However, the coalescing of the two inductors adjoining each diode into a single inductor or the presence of a mutual inductive effect, as in oscillators with lumped parameter elements, does not significantly alter the operation and requires but a slight modification in the analysis. The circuit load is represented by two resistors, each of resistance r_1 in series with the secondary windings of two ideal, unity turns ratio transformers 2-1 and 2-2, respective ones of whose primary windings are connected in series with respective ones of either of the series combined inductors. This typifies one of the many ways in which the load may be coupled to the oscillator. A shunt branch 3 containing a bias voltage source and a mode suppression resistor of resistance r_2 is connected between the mid-points 4 and 5 of the series combined inductors. The bias voltage V is of such magnitude that a negative resistance characteristic is provided at the diode terminals in order to cancel the dissipative resistance of the load and assure sustained oscillations. The mode suppression resistor has associated with it an inductance L_2 , generally of small magnitude, represented by a series inductor.

It is immediately apparent that two oscillatory modes may exist simultaneously in the circuit of FIG. 1. In the first of these, the push-pull mode, the diodes oscillate in phase opposition, that is, when the voltage at one is positive with respect to the common point of the circuit, the voltage at a comparable terminal of the other is negative. Typical loop currents I_p , indicated by solid arrows, flow in the same clock sense. There is no net

alternating current in the shunt branch 3 so that the mid-points 4 and 5 of the series combined inductors are at a common potential and the mode suppression resistance r_2 has no effect on the push-pull mode currents. By contrast for the unison mode, in which the diodes oscillate in phase coincidence, typical loop currents I_u , indicated by dashed arrows, flow in opposed clock senses so that no unison mode voltage is developed in either load resistance r_1 . These currents I_u converge in the shunt branch 3 containing the mode suppression resistor and establish an alternating voltage across it. Consequently, variations in the load resistance have no effect on the unison mode and regulation of the magnitude of the mode suppression resistance r_2 is of no consequence to the push-pull mode. It is this mode separability which makes possible the adjustment of the magnitude of the parameters associated with the elements forming the oscillator of FIG. 1 so that the unison mode currents I_u are damped out while the push-pull mode currents I_p provide sustained oscillations.

Each of the modes is associated with a distinct equivalent circuit as indicated in FIGS. 2a and 2b, both showing a voltage-controlled diode, represented by the parallel combination of a capacitor of capacitance C and a resistor of negative resistance $-R$, connected in series with a resistor of resistance r and an inductor of inductance L . In matching the parameters of FIGS. 2a and 2b with those of FIG. 1, the branches of the latter containing diodes may be consolidated after being taken in series for the push-pull mode, because of the zero voltage across the shunt branch 3, and in parallel for the unison mode, because of the convergence of currents in the shunt branch. Accordingly, for the push-pull mode circuit of FIG. 2a, the inductance L and the resistance r are respectively equivalent to twice the inductance L_1 and twice the load resistance r_1 in FIG. 1, the latter resistance being reflected into the path of the push-pull mode currents I_p by the ideal coupling transformers 2-1 and 2-2. The capacitance C and the negative resistance $-R$ are respectively equivalent to one-half of capacitance C_1 and twice negative resistance $-R_1$, the latter quantities being associated with each one of the negative resistance diodes 1-1 and 1-2 of FIG. 1. For the unison mode circuit of FIG. 2b, on the other hand, the inductance L is the combination of one-half of the inductance L_1 and the inductance L_2 of FIG. 1 while the resistance r is that of the mode suppression resistance r_2 in FIG. 1. The capacitance C and the negative resistance $-R$ become, respectively, twice the capacitance C_1 and one-half the negative resistance $-R_1$, these latter parameters again being associated with each one of the negative resistance diodes 1-1 and 1-2 of FIG. 1. Other circuit effects may be incorporated into the equivalent circuits of FIGS. 2a and 2b, such as by supplementing the resistance r by the parasitic resistance commonly found in semiconductor diodes and augmenting the inductance L by the mutual inductive effect created by the coupling of the load to the oscillator.

The way in which an oscillatory mode may build up or be damped out in the circuits of FIGS. 2a and 2b is determined from the complex frequency s given by Equation 1:

$$s = \sigma \pm j\omega = \sigma \pm j\sqrt{\beta - \sigma^2} \quad (1)$$

where

$$\sigma = \frac{1}{2} \left(\frac{1}{CR} - \frac{r}{L} \right) \quad (1a)$$

$$\beta = \frac{1}{LC} \left(1 - \frac{r}{R} \right) \quad (1b)$$

and L , C , R , r are respectively the inductive, capacitive, negative resistive and positive resistive parameters whose exact magnitudes depend upon whether the push-pull

5

or the unison mode is being analyzed. The corresponding time response, taken without regard to amplitude or phase considerations, is indicated in Equation 2:

$$i = e^{\sigma t} \sin \omega t \quad (2)$$

where

i = circuit current of FIGS. 2a and 2b, normalized to unit amplitude,

t = time,

and

e = base of natural logarithms.

Taken together, Equations 1 and 2 indicate that transient time-varying currents decay exponentially provided that

$$\sigma < 0, \text{ that is, } \frac{r}{L} > \frac{1}{RC} \text{ or } \frac{r}{R} > \frac{L}{R^2 C}$$

and

$$\beta > 0, \text{ that is, } \frac{r}{R} < 1$$

The latter condition follows from the fact that otherwise the wave would be an increasing exponential inasmuch as the square root of the radicand in Equation 1 would be greater than σ . In other words and undesired unison mode is suppressed if the resistance ratio r/R for the circuit of FIG. 2b satisfies Equation 3:

$$1 > \frac{r}{R} > \frac{L}{R^2 C} \quad (3)$$

Since Equation 1 contains four parameters, each separately variable, a helpful reformulation is made in terms of but two parameters: r/R and Q . Q is measured by the quotient of the negative resistance and the resonant reactance of its associated capacitance; thus, it is an impedance ratio equal to $\omega_0 RC$ where ω_0 is

$$\frac{1}{\sqrt{LC}}$$

The possible transient conditions for the circuits of FIGS. 2a and 2b are shown in terms of the new parameters r/R and Q in FIG. 3. Region I, wherein the currents of latent modes decay exponentially, is bounded as prescribed by Equation 4, which is Equation 3 recast in terms of Q :

$$1 > \frac{r}{R} > \frac{1}{Q^2} = \frac{L}{R^2 C} \quad (4)$$

For operation within Region II, wherein sinusoidal oscillations build up, the conditions of Equations 5a and 5b must be satisfied:

$$\frac{r}{R} < \left(\frac{2}{Q} - \frac{1}{Q^2} \right) \quad (5a)$$

and

$$\frac{r}{R} < \frac{1}{Q^2} \quad (5b)$$

Equation 5a is established by noting that the waveform of the current in Equation 2 is of a sinusoidal variety provided that the radicand of Equation 1 is positive, that is,

$$\sigma^2 < \beta \text{ or } \frac{1}{4} \left(\frac{1}{CR} - \frac{r}{L} \right)^2 < \frac{1}{LC} \left(1 - \frac{r}{R} \right)$$

which can be simplified to:

$$r^2 + \left(\frac{2L}{CR} \right) r + \left(\frac{L^2 - 4R^2 CL}{C^2 R^2} \right) < 0$$

so that

$$\frac{r}{R} < \frac{2}{R} \sqrt{\frac{L}{C}} - \frac{L}{CR^2} = \frac{2}{Q} - \frac{1}{Q^2}$$

The plot of Equation 5a in FIG. 3 demonstrates that for values of Q greater than unity, Region I is divided into two subregions, the one delimited by Equations

6

5a and 5b being for sinusoidal oscillations which decay exponentially.

Throughout the remaining Region III, the frequency variable s in Equation 1 is a positive real quantity and currents build up nonsinusoidally. In this region, if

$$\frac{r}{R} > 1$$

the buildup produces oscillations of the relaxation variety, with maximum voltage excursions limited by the positive resistance regions of the diode current-voltage characteristic.

It will now be demonstrated that the parameters of the oscillator in FIG. 1 may be adjusted so that push-pull mode oscillatory currents are sustained at the same time that unison mode currents are damped out in spite of differences in the magnitudes of the impedance ratios Q_1 and Q_2 for the respective modes.

Assuming Q_1 and Q_2 greater than unity, Equation 5b for the push-pull mode takes the form:

$$\frac{r_1}{R_1} < \frac{1}{Q_1^2} = \frac{\frac{L_1}{2}}{\left(\frac{R_1^2}{2} \right) (2C_1)} = \frac{L_1}{R_1^2 C_1}$$

or

$$r_1 < \frac{L_1}{R_1 C_1} \quad (6a)$$

and the corresponding Equation 4 for the unison mode becomes:

$$\frac{r_2}{R_1} > \frac{1}{Q_2^2} = \frac{4L_2 + 2L_1}{(2R_1)^2 \left(\frac{C_1}{2} \right)} = \frac{L_1}{R_1^2 C_1}$$

or

$$r_2 > \frac{\frac{L_1}{2} + L_2}{R_1 C_1} \quad (6b)$$

provided

$$r_2 < \frac{R_1}{2}$$

Because of the separability of the circuit modes the load resistance r_1 and the mode suppression r_2 are placeable in circuit locations where they do not interact with each other, thus allowing Equations 6a and 6b to be satisfied simultaneously so that the oscillator of FIG. 1 exhibits sustained sinusoidal push-pull mode oscillations while simultaneously damping unison mode energy.

When Q_1 equals Q_2 , as where the parasitic inductance L_2 may be neglected, the condition for the simultaneity of undesired mode suppression and desired mode oscillations is given by Equation 6c:

$$r_1 < \frac{R_1}{Q^2} < 2r_2 \quad (6c)$$

when

$$Q > 1 \text{ and } \frac{2r_2}{R} < 1$$

Of course, as indicated by FIG. 3, Q_2 must be greater than unity if the unison mode energy is to be damped out, but Q_1 may extend below unity as far as a limiting magnitude of one-half, thus being in a range for which the magnitude of the load resistance r_2 is determined as prescribed by Equation 5a.

The principles discussed in conjunction with FIGS. 2a and 2b and FIG. 3 may be applied directly, in keeping with the invention, to the design of a two-diode coaxial cavity oscillator of the kind shown in FIG. 4a. A coaxial cavity is established by connecting short-circuiting end caps 10-1 and 10-2 between an inner conductor

11 and a concentric outer conductor 12 with one cap at each extremity of the inner conductor axis z . Two voltage-controlled negative resistance spot diodes 1-1 and 1-2, each having its axis aligned with that of the inner conductor, are symmetrically disposed within the cavity and similarly poled with respect to the cavity bisecting plane 17 normal to the inner and outer conductors. The diodes may be of the kind suggested earlier. A mode suppression resistor 13 lying in the cavity bisecting plane 17 makes direct electrical contact with the inner conductor 11 and extends outward from the cavity through an aperture in the outer conductor 12 from which it is spaced by an annular dielectric sheath 14 providing a by-pass capacitance of large magnitude in order to prevent further undesired modes involving the inductance of the leads of the power supply 15 connected between the resistor 13 and outer conductor 12 to furnish a bias supply voltage V . Energy is extracted from the cavity through a coupling aperture 16 in the wall of the outer conductor 12 in the vicinity of its mid-section. The current flow for the two modes supportable by the oscillator is indicated by solid arrows for the push-pull mode and dashed arrows for the unison mode. The corresponding axial current distributions are plotted in FIG. 4b in a plane containing the axis of the inner conductor. The solid line identifying the push-pull mode current I_p rises from zero at each end of the cavity to a maximum at its mid-section while the dashed line marking the unison mode current I_u rises less rapidly from zero and reaches an appreciable magnitude at the cavity mid-section where it changes phase to account for the large current flow in the mode suppression resistor 13. Since the current and voltage distributions are in space quadrature throughout the major part of the cavity, the push-pull voltage is zero in the cavity bisecting plane 17 with the result that the mode suppression resistor 13 is placed where it will absorb the minimum push-pull mode energy. Furthermore, the coupling aperture 16 is located where maximum push-pull energy is extracted by way of the large magnitude magnetic field associated with the push-pull current but where the unison mode energy is zero.

In spite of its having distributed parameters, the coaxial cavity oscillator of FIG. 4 may be analyzed by using the lumped parameter circuit of FIG. 1 with the inductance L_1 taken as one-half of the cavity inductance of FIG. 4. The resistive magnitude r_2 of the mode suppression resistor 13 is calculated by reference to FIG. 2b after supplementing resistance r by one-half of the parasitic resistance r_p of a single diode. To be damped out the unison mode must satisfy of constraints of Equation 7 which is a variation of Equation 4:

$$1 > \frac{r}{R} = \frac{r_p + 2r_2}{R_1} > \frac{1}{Q_2^2} \quad (7)$$

where symbols are as for Equation 6b.

Contemporaneous sustained sinusoidal oscillations occur in the push-pull mode if the coupling is adjusted so that the load resistance $2r_1$ satisfies the requirements of Equations 5a and 5b, as rewritten in Equations 8a and 8b:

$$\frac{r_1 + r_p}{R_1} < \frac{2}{Q_1} - \frac{1}{Q_1^2} \quad (8a)$$

and

$$\frac{r_1 + r_p}{R_1} < \frac{1}{Q_1^2} \quad (8b)$$

where symbols are as for Equation 6a. In the calculation of Q_1 , the coupling inductance is taken into account.

According to the invention a strip-line oscillator may be evolved as shown in FIG. 5. Two similarly poled spot diodes 1-1 and 1-2, which may be of the kind used in the coaxial cavity oscillator of FIG. 4, are perpendic-

ularly positioned between parallel conducting plates 20-1 and 20-2 that facilitate mode separation and have a bias supply 21 of voltage V connected therebetween. The diodes are mounted on pedestals 21-1 and 22-2 which taken together with the diodes from the conductors of a two-wire transmission line. The diode axes 23-1 and 23-2 perpendicular to the plates lie in a plane 25 designated the diode plane. On each side of the diode plane 25 and displaced therefrom and parallel thereto, is a distinct one of two mode suppression resistors 24-1 and 24-2, in the form of a film or slab, electrically connected between the strip-line conductors 20-1 and 20-2. The push-pull mode currents I_p , whose flow is indicated by solid arrows, surge back and forth between the diodes along surfaces of the conducting plates. The resultant vector established by energizing these currents over the surfaces is in a direction parallel with the diode plane 25. The unison mode current I_u , designated by dotted arrows, flow in a direction normal to the diode plane 25. As a result, the two modes are orthogonal, but it is also necessary to provide that the width of the conducting plates 20-1 and 20-2 in the direction of the diode plane 25 is less than one-half wavelength at the frequency of oscillations, thereby establishing a cut-off condition for the push-pull mode currents I_p and preventing the propagation of their energies between the strip-line conductors in the lengthwise direction. By virtue of the separation of modes, an undesired current component, for example, that of the unison mode, is attenuated by the placement of a resistive film normal to its paths. One such film is located on each side of the diode plane and sufficiently displaced therefrom to prevent undue interference with the currents of the desired mode.

As with the oscillator of FIG. 4 the circuits of FIGS. 2a and 2b may be used in the analysis of the existing modes in FIG. 5. For the push-pull mode the inductance L of FIG. 2a is essentially that of a two-wire transmission line bounded by two metallic plates and as such depends upon the diameters of the transmission line conductors and their distances of separation. The resistance r is the sum of the load resistance coupled into the transverse electromagnetic field between the two diodes near the edge of the conducting plates where push-pull mode currents flow and twice the parasitic resistance associated with a single diode. When the restrictions of Equations 5a and 5b are satisfied, sustained push-pull mode oscillations ensue. In determining the unison mode parameters for the circuit of FIG. 2b, the inductance L is often made up of two components. The first of these may be approximated by assuming a coaxial line field configuration extending outward from the diodes as far as the distance of separation between them. There is an additional inductive component attributable to the strip line if the mode suppression resistance is of small magnitude. This effect is eliminated if the mode suppression resistor is matched to the characteristic impedance of the strip lines. It becomes capacitive when the mode suppression resistor is of large magnitude and the equivalent circuit of FIG. 2b must be modified accordingly. However, for the typical case where the mode suppression resistor is of small magnitude, so that the resistance r of FIG. 2b is the summation of one-half of both the mode suppression resistance and the diode parasitic resistance, the conditions for the suppression of the unison mode are given directly by Equation 4.

The invention is not confined to oscillators employing spot diodes. In the interest of greater power capability the p-n junctions of such diodes may be extended in depth while maintaining narrow cross sections in order to keep their capacitive magnitudes per unit length small. As a consequence of their extended lengths, line diodes are able to support standing wave modes which must be suppressed in the manner taught by the invention. A strip-line oscillator with two line diodes could be produced by extending the p-n junctions of the diodes in the

oscillator of FIG. 5 in a direction normal to the plane containing the pre-existing diode axes. In practice, it is simpler to fabricate a diode assembly of the kind depicted in FIG. 6a in which two voltage-controlled negative resistance line diodes 1-1 and 1-2 forming a diode pair are perpendicularly positioned between parallel conducting plates 30-1 and 30-2 and activated by a shunting bias source 37 of voltage V. The substantially parallel p-n junctions 31-1 and 31-2 of the diode pair result from alloying the top surfaces of two coextensive ridges 32-1 and 32-2, rising out of the base plate 30-2 with a semiconductor slab 33 integral with the cover plate 30-1 near its mid-section. As in FIG. 5 there are two resistive slabs or films 34-1 and 34-2 between the plates, one at each flank of the diode pair to attenuate unison mode currents I_u whose paths are indicated by dashed arrows in the plane of the cover plate 30-1. While the flow of circulating currents between the two ridges provides sufficient frequency determining inductance, there is in FIG. 6a an additional inductive effect created by the cavity 35 underlying the surface of the base plate 30-2. Two channels 36-1 and 36-2, one on each flank of the diode pair, serve to confine the movement, over the physical surfaces of the oscillator, of the desired push-pull mode currents I_p , identified by solid arrows, to a direction substantially normal to the diode p-n junctions 31-2 and 31-1. This effect is enhanced by making plates of greater length than width. The two kinds of standing wave modes supportable by the oscillator because of the extended length of its p-n junctions 31-1 and 31-2 are shown in the two successive planes of FIGS. 6b and 6c, each parallel with the cover plate but successively displaced therefrom. The planes of FIGS. 6b and 6c, respectively, show the distributions of the unison standing wave mode currents I_{uc} and of the push-pull standing wave mode currents I_{pc} along the p-n junctions 31-1 and 31-2 of the line diodes 1-1 and 1-2. Because of the close spacing of the conductor plates 30-1 and 30-2 in the regions 38-1 and 38-2 extending outward from the p-n junctions 31-1 and 31-2, the circulating currents of both standing wave modes are provided with low inductance paths, thus raising their frequencies to that part of the spectrum where they are easily attenuated.

The equivalent circuit of FIG. 2b is used directly in analyzing the unison mode of FIG. 6a. The inductance L of the former is equated to one-half of the inductance of one of the channels in the oscillator base plate. When the mode suppression resistors 34-1 and 34-2 are matched to the strip line or placed physically close to the channels 36-1 and 36-2, the resistance r is the parallel combination of the resistances provided by the mode suppression resistors 34-1 and 34-2. As before, the conditions for the attenuation of the unison are calculated by applying Equation 4, after modifying the magnitude of the capacitance C by taking into account the capacitance C_s attributable to the close spacing of the strip-line conductors 30-1 and 30-2 in the vicinity of the diode p-n junctions 31-1 and 31-2.

For the push-pull and standing wave modes it is necessary to modify the circuit of FIG. 2a as shown in FIG. 7. In the core part of the circuit, which is the same as that of FIG. 2a, the resistance r is represented by the summation of the cavity resistance r_c and the semiconductor parasitic resistance r_p between the two diode p-n junctions 31-1 and 31-2. Disposed in shunt with the core circuit is a branch of two elements, the first representing the impedance $\pm jX_m$ of the standing wave mode suppression regions 38-1 and 38-2 which are respectively capacitive $-jX_m$ and inductive $+jX_m$ for the push-pull and standing wave modes. This is in series with a resistance r' equivalent to twice the skin effect resistance r_m of the mode suppression regions 38-1 and 38-2 in series with twice the parasitic semiconductor resistance r_p extending between one of the diode p-n junctions 31-1 and 31-2 and the metallic surface of the cover plate 30-1. When the oscil-

lator operates in its push-pull mode, there additionally appears across the mode suppression impedance $\pm jX_m$ the load resistance R_0 . All of the parameters of FIG. 7 are computed on a per unit length basis. The suppression of the standing wave modes is controlled by regulating the spacing d between the conductors and thereby changing the inductive magnitude associated with the mode suppression impedance. This alteration of the spacing d also influences the skin effect resistance r_m , since its magnitude increases with frequency. The exact spacing d of the conductors is determined by omitting the load resistance R_0 from the circuit of FIG. 7, calculating the total impedance as seen at the terminals of the mode suppression impedance and requiring the real part of the expression so computed to be greater than zero.

The conditions for sustained push-pull mode oscillations are established in a similar fashion except that the load resistance R_0 is retained in the equivalent circuit of FIG. 7 and the real part of the total impedance must be less than zero.

The oscillators of FIGS. 5 and 6a may have their power coupled out in a variety of ways. A typical technique is to place them within a waveguide as has been done with the oscillator of FIG. 6a in the output circuit of FIG. 8. The cover plate 30-1 of the oscillator becomes the short-circuiting termination 40 transverse to the axis of propagation 44 of the waveguide 41. Coupling to the waveguide 41 is effected by the push-pull mode energy of the oscillator which creates an electric field E that extends beyond the edges of the base plate 42 and becomes established in the waveguide. A bias supply 43 of voltage V is connected between the base plate 42 of the oscillator and the waveguide termination 40 through an aperture 45 in the latter in order to cause minimal discontinuities within the guide 41. A post 46 suspended from the upper wall of the waveguide and displaced from the base plate 42 of the oscillator is introduced to control the coupling and allow matching of the oscillator to its load.

While the invention has been illustrated as embodied in a wide variety of oscillator circuits, which by definition have output, but no input, terminals, it will be readily appreciated that the invention can be practiced in numerous other ways. For example, if all modes are suppressed below their thresholds of oscillation, the residual negative resistance provided in accordance with the invention can be turned to account to offset losses elsewhere in a system. Still other uses will occur to those skilled in the art.

What is claimed is:

1. Apparatus which comprises a network of three branches extending between a first common point and a second common point, the first branch including a first negative resistance diode and first reactive means, the second branch including a second, similar, negative resistance diode and second reactive means, said diodes being similarly poled with respect to said common points, the third branch including an energy source for biasing said diodes to preassigned regions of their current voltage characteristics, whereby oscillations may take place in either of at least two modes, said third branch also including an attenuator for suppressing oscillations of at least one of said modes.

2. Apparatus characterized by latent current modes with distinct spatial distributions attributable to the physical separation of the active elements of said oscillator, which comprises two voltage-controlled negative resistance diodes, each being an active element of said oscillator and having a first terminal and a second terminal, distributed parameter frequency determining inductive means interconnecting respective ones of said first terminals and respective ones of said second terminals, forming a closed circuit with said diodes and enabling said frequency determining inductive means to act in concert with capacitance in shunt with said diodes, bias means connected in shunt with both of said diodes and activating said diodes in those regions of their current voltage characteristics

11

wherein said diodes display negative resistances, rendering said oscillator capable of providing sustained oscillations in at least one of said latent modes, and coupling means for electrically connecting a load resistance to said circuit in that portion thereof characterized by the presence of substantial desired mode currents and the absence of substantial undesired mode currents, the magnitude of said load resistance being adjusted to assure sustained oscillations by said desired mode currents whereby undesired mode energy is prevented from appearing in the output of said circuit.

3. Apparatus as defined in claim 2 wherein the magnitude of said load resistance r_1 is so proportioned that it simultaneously satisfies the relations:

$$r_1 < \frac{2R_1}{Q_1} - \frac{R_1}{Q_1^2} - r_p$$

and

$$r_1 < \frac{R_1}{Q_1^2} - r_p$$

where

r_p = the resistive magnitude of a lumped parameter resistor representing the collective effect of parasitic resistance in said circuit,

R_1 = the resistive magnitude of a lumped parameter resistor representing the negative resistance associated with each one of said diodes,

and

Q_1 = the impedance ratio for the desired mode currents of each of said diodes,

said impedance ratio being equal to $\omega_d R_1 C$ for which C represents the collective shunt capacitance associated with each one of said diodes and ω_d equals the oscillatory frequency of said desired mode currents as established by the interaction of said inductive means and said shunt capacitance.

4. Apparatus characterized by latent current modes with distinct spatial distributions attributable to the physical separation of the active elements of said oscillator, which comprises two voltage-controlled negative resistance diodes, each being an active element of said oscillator and having a first terminal and a second terminal, distributed parameter frequency determining inductive means interconnecting respective ones of said first terminals and respective ones of said second terminals, forming a closed circuit with said diodes and enabling said frequency determining inductive means to act in concert with capacitance in shunt with said diodes, bias means connected in shunt with both of said diodes and activating said diodes in those regions of their current voltage characteristics wherein said diodes display negative resistances, rendering said oscillator capable of providing sustained oscillations in at least one of said latent modes, coupling means for electrically connecting a load resistance to said circuit in that portion thereof characterized by the presence of substantial desired mode currents and the absence of substantial undesired mode currents, the magnitude of said load resistance being adjusted to assure sustained oscillations by said desired mode currents, and resistive means connected in shunt with said diodes in that portion of said circuit characterized by the presence of substantial undesired mode currents and the absence of substantial desired mode currents, said resistive means being proportioned to cause the currents of said undesired mode to be rapidly damped out, whereby said undesired mode currents are prevented from appearing in the output of said circuit and acting as a load on said desired mode energy so that said oscillator is constrained to operate in its desired mode.

5. Apparatus as defined in claim 4 wherein said resistive means comprises at least one resistive element of resistive magnitude lying within the range defined at the upper extremity thereof by the product of an index k and the magnitude of an upper bound resistance U and at

12

the lower extremity thereof by the product of said index k and the magnitude of a lower bound resistance L , said index being one-half for the employment of a single resistive element and unity for the employment of two like resistive elements, said lower bound resistive magnitude L and said upper bound resistive magnitude U being respectively defined by the relations:

$$L = R_1 - r_p$$

$$U = \frac{R_1}{Q_2^2} - r_p$$

where

r_p = the resistive magnitude of a lumped parameter resistor representing the collective effect of parasitic resistance in said circuit,

R_1 = the resistive magnitude of a lumped parameter resistor representing the negative resistance associated with each one of said diodes,

20 and

Q_2 = the impedance ratio for the undesired mode currents of each of said diodes,

said impedance ratio Q_2 being equal to $\omega_u R_1 C$ for which C represents the collective shunt capacitance associated with each one of said diodes and ω_u equals the oscillatory frequency of said undesired mode currents as established by the interaction of said inductive means and said shunt capacitance whereby the resistive magnitude of said resistive means is confined to that region of the graphical characteristic interrelating r_2 , R_1 and Q_2 wherein said undesired mode currents are either damped oscillations or exponentially decaying transient.

6. Apparatus as defined in claim 4 wherein said diodes support undesired standing wave modes generated by the flow of circulating currents from one locality to another locality of said diodes, further including mode suppression means in shunt with said diodes for providing low inductance paths for said circulating currents and raising the frequencies thereof to that part of the frequency spectrum wherein said circulating currents are rapidly damped out, whereby said standing wave mode currents are prevented from appearing in the output of said circuit and acting as a load on said desired mode energy with the result that said oscillator is further constrained to operate in its desired mode.

7. Apparatus as defined in claim 6 wherein each of said diodes has an elongated junction, the elongation thereof being in a direction normal to that defined by the flow of desired mode currents between said diodes, the power capability of each of said diodes being enhanced thereby, subject to being impaired by the presence of said circulating currents, and said mode suppression means comprises, for each of said diodes, closely spaced conducting surfaces commencing at said junction, coextensive therewith and extending outward therefrom generally paralleling the plane containing said elongated junction.

8. Apparatus as defined in claim 2 wherein said coupling means comprises a waveguide section, said oscillator being arranged therein so that the portion of said oscillator characterized by the presence of substantial desired mode currents is capable of exciting said waveguide section in one of its supportable oscillatory modes.

9. The apparatus as defined in claim 7 further including mode channeling inductive means at the flanks of said extended junctions whereby said desired mode currents of said oscillator are confined to flow in a direction substantially normal to said extended junctions by virtue of the high impedance path presented to the flow of said desired mode currents by said mode channeling inductive means.

10. A high frequency push-pull oscillator which comprises two voltage-controlled negative resistance diodes, each having a first terminal and a second terminal, said first terminals being interconnected, frequency determining inductive means interconnecting said second termi-

13

nals, bias means connected in shunt with said diodes, resistive means connected in shunt with said diodes for damping out the unison mode currents generated thereby, and mode suppression means connected in shunt with said diodes for raising the frequencies of standing wave modes along said diodes to that part of the frequency spectrum for which the incipient oscillations of said standing wave modes are rapidly damped out, whereby said oscillator is constrained to operate in its push-pull mode.

11. Apparatus as defined in claim 10 wherein said frequency determining inductive means is a coaxial cavity having an inner conductor and a concentric outer conductor and the shunt connection of said resistive means is between said inner conductor and said outer conductor.

12. Apparatus as defined in claim 10 wherein said frequency determining inductive means comprises a section of a parallel wire transmission line bounded at both extremities thereof by transverse metallic plates and said resistive means comprises two resistive elements electrically connected between said plates, one of said elements being disposed on each side of the plane normal to said plates and containing both conductors of said transmission line.

13. Apparatus as defined in claim 10 wherein each of said diodes has an extended p-n junction, said resistive means comprises a resistive element at each extremity of said extended junction and said mode suppression means comprises closely spaced, substantially parallel conducting surfaces straddling said extended junction for each of said diodes.

14. Apparatus which comprises

- a first conductive structure having a surface,
- a second conductive structure having a surface,
- a first negative resistance element interconnecting the surface of said first conductive structure with the surface of said second conductive structure,
- a second negative resistance element, displaced with respect to said first negative element, interconnecting the surface of said first conductive structure with the surface of said second conductive structure,
- and an attenuating structure, orthogonally displaced with respect to the first and second negative resistance elements, interconnecting the surface of said

14

first conductive structure with the surface of said second conductive structure.

15. Apparatus which comprises

- a first conductive structure having a surface,
- a second conductive structure having a surface,
- a first negative resistance element interconnecting the surface of said first conductive structure with the surface of said second conductive structure,
- a second negative resistance element, displaced with respect to said first negative resistance element, interconnecting the surface of said first conductive structure with the surface of said second conductive structure,

means interconnecting said first structure with said second structure for establishing distinctive, orthogonal distributions of current and voltage between the first and second negative elements,

and means interconnecting said first structure with the second for controlling one of said distributions of current and voltage.

16. Apparatus which comprises

- a first negative resistance diode,
- a second negative resistance diode connected in shunt with the first,

activating means connected in shunt with said diodes for causing them to be operable at a plurality of frequencies,

first resistive means connected in shunt with said diodes for loading them at one frequency of said plurality, and second resistive means connected in series with said diodes for loading them at another frequency of said plurality different from the first.

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